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*Research Article*

# Mechanical and Wear Behaviour of Nano-Fly Ash Particle-Reinforced Mg Metal Matrix Composites Fabricated by Stir Casting Technique

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In recent years, magnesium-based alloys and composites have great attention in automobile, structural, and biomedical industries due to their desirable characteristics such as lower density, low elastic modulus, high specific strength, better damping properties, and excellent castability. The pure magnesium was used as a matrix material and reinforced with fly ash fillers of different compositions with a weight percentage of 2.5%, 5%, and 7.5% to compare with the pure magnesium. The three different weights (wt%) of fly ash/Mg samples were prepared using the bottom pouring stir casting method. Fabricated samples sliding wear characteristics and mechanical behaviour (ASTM standard) were studied. Wear, tensile, and hardness results portray that 7.5 wt% fly ash composites possess better elongation and hardness and good wear resistance. The tensile strength values were improved by 42% in sample 4 compared with pure Mg. Hardness values were also improved by 21% in sample 4 compared with pure Mg. The wear rate and coefficient of friction are also reduced by the increased weight percentage of fly ash reinforcement. SEM images display casted pure magnesium's morphology and wear-tested samples' worn surface characteristics.

## 1. Introduction

Nowadays, tremendous demand for lightweight metal matrix composites for structural applications in biomedical, structural, and automobile industries [1]. In the new lightweight materials, more energy-efficient and recyclable magnesium is one of the best dominant materials which replaces all existing materials. Pure magnesium is 75% lighter than steel and 33% lighter weight than aluminium. The report states that overall fuel savings can be 20 to 30% by replacing aluminium with magnesium-based materials in the automotive industry [2]. The magnesium alloy system has combinations of Al, Mn, Zn, Zr, and rare earth material constituents. However, the available magnesium alloy system has limitations, such as low strength and poor flexibility. Magnesium has less flexibility due to its hexagonal closed pack structure and possesses only three independent slip systems [3]. In order to overcome those limitations and enhance their mechanical and wear properties, the addition of micron-scale fly ash is preferred among industrialists.

Recent studies have shown that adding reinforcements such as SiC, $Al_2O_3$, MgO, $ZrO_2$, and CNTS improves mechanical properties and ductility. Fly ash is the most easily available and inexpensive material, and land pollution can be limited with proper utilisation. It greatly impacts the environmental effect of thermal power plants and other combustion processes of industries that use coal as fuel [4]. Fly ash can be categorized into solid precipitator and cenosphere types. The fly ash constitutes the major composition of $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and CaO. The yearly production estimation of fly ash worldwide is 900-1000 million tonnes (fly ash and slag) [5, 6]. Dinaharan et al. produced AZ31/10 vol% FA MMC using conventional stir casting and compared the same composites with friction stir processing. They reported that the wear and hardness of the two fabrication methods show that the huge differences are due to undesirable microstructures [7]. Kondaiah et al. fabricated AZ31/fly ash composites using a friction stir process and stated increased hardness and better wear characteristics [8]. Viswanath et al. developed AZ91/SiC composites (5, 10, 20, and 25 wt%) using stir casting. They observed improved creep resistance in 15, 20, and 25 wt% of SiC composites [9]. Matina et al. fabricated pure magnesium/SiC and AZ80/SiC composites by stir casting. They proved that hardness values were increasing according to the increment percentage of SiC reinforcement [10]. Rohatgi et al. demonstrated that the addition of fly ash in AZ91 magnesium alloys enhanced electrical resistivity and electromagnetic interference shield [11].

Lim et al. developed AZ91/D-fly ash composites by die casting method. They reported that composite density decreased when the fly ash percentage increased, and the maximum tensile strength was achieved in 5 wt% reinforced fly ash composites [12]. Hassan et al. investigated the wear behaviour of Mg-/SiCp-reinforced composites. They achieved that the composites improved wear resistance up to 15-30% due to their excellent load-bearing capacity. They stated that Young's modulus decreased with increased fly ash reinforcement percentage [13, 14]. Al-Mg-Cu alloys were manufactured using various weight percentages of Cu using powder metallurgy. The mechanically mixed layer (MML) formations result in counter face disk wear rather than material wear which contradicts the overall results [2]. Composting detected an almost 5-7% reduction in porosity and enhanced mechanical properties to stir casting. However, it showed specific impairments in the development at rising temperatures [15].

The liquid state synthesis route is a simple and inexpensive method to produce complex geometry shapes in metal matrix composites. After reviewing the above literature, it was noticed that so much research is needed to be conducted on fly ash-reinforced magnesium metal matrix composites to explore their advantages over other traditional filler materials. The present work is aimed at improving the mechanical properties and wear behaviour, conducting microstructural studies of Mg-fly ash-reinforced composites, and comparing configuration with pure magnesium.

Table 1: Chemical composition as-received magnesium (in wt%).

| Element | Mg | Al | Si | Fe | Cu | Mn | Cl |
|---|---|---|---|---|---|---|---|
| wt% | 99.9277 | 0.017 | 0.022 | 0.0012 | 0.0001 | 0.024 | 0.004 |

Table 2: Chemical composition of as-received fly ash (in wt%).

| Element | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $MnO_2$ | $K_2O$ | $TiO_2$ | LOI |
|---|---|---|---|---|---|---|---|---|
| wt% | 50.5 | 22.54 | 7.3 | 5.1 | 1.0 | 0.5 | 0.35 | Balance |

Table 3: Test samples and their reinforcement percentages.

| Test samples | The weight percentage of magnesium and fly ash |
|---|---|
| Sample 1 (PMg) | Pure magnesium |
| Sample 2 | Mg 97.5% + fly ash 2.5% |
| Sample 3 | Mg 95% + fly ash 5% |
| Sample 4 | Mg 92.5% + fly ash 7.5% |

## 2. Materials and Methods

*2.1. Materials.* Pure magnesium is supplied by Shree Bajrang sales private limited, Raipur. Magnesium composition includes 99.9277% pure magnesium and the remaining small amount of Al, Si, Fe, Cu, Mn, etc. The detailed percentage of compositions is shown in Table 1. Fly ash was collected from the Mettur Thermal Power Station, a coal-fired electric power station located in Mettur, Tamil Nadu [16]. The detailed chemical composition of as-received fly ash percentages is shown in Table 2. The average particle size of fly ash is 10 nm [17].

### *2.2. Experimental Procedure*

*2.2.1. Stir Casting.* The composites were prepared by the liquid state stir casting method. Stir casting is a cost-effective and relatively simplest method for producing metal matrix composites. First, a graphite crucible was melted, and the commercially available premeasured quantity of pure magnesium metal was cast by an electrical resistance furnace [18]. Then, magnesium samples as received from the supplier (unreinforced) and magnesium composites were prepared with three fly ash reinforcements (2.5, 5, and 7.5 wt%) shown in Table 3. The high-purity magnesium (99.93%) melted in a graphite crucible using an electrical resistance heating at 750°C. The fly ash particles were preheated to 300°C to remove the moisture content for two hours [19]. The fly ash particles were added during vortex formation due to the stirring process in the melt [20]. The weight percentage of 2.5, 5, and 7.5% fly ash was added into the magnesium matrix under the protected inert atmosphere

Figure 1: Experimental setup of stir casting furnace.

Figure 2: Fabricated tensile and wear samples.

of argon gas. Experimental setup of stir casting furnace is shown in Figure 1.

The steel impeller was used to properly distribute the preheated reinforcement fly ash with the matrix material. The stirring rod rotates at the speed of 750 rpm and stirs continuously for 10 minutes. Then immediately, the molten metal was poured into a 300°C preheated graphite mould to obtain the castings [21]. Figure 2 shows the fabricated tensile and wear samples.

### *2.3. Mechanical Characterization*

*2.3.1. Tensile Test.* The tensile strength of fabricated samples was measured at room temperature using Instron -4208 Universal Testing Machine (UTM). ASTM standard E8M-09 was followed to prepare cylindrical cross-section tensile test specimens. Every three specimens were prepared for pure monolithic magnesium and Mg/fly ash-reinforced composite. The tensile strength results were based on the three samples' average results. Crosshead speed has been considered as 0.5 mm/min [22].

Figure 3: Pin on disc apparatus.

*2.3.2. Microhardness Test.* Microhardness tests were conducted by using the Vickers microhardness instrument. Hardness values are measured at five different places in every sample, and average values are tabulated. ASTM E384 standard was followed for the hardness test [23].

*2.3.3. Low-Velocity Impact Test.* Measuring the energy absorption nature of any metal used as an industrial counterpart is important. The proposed fabricated samples were tested for their low-velocity energy absorption. The pure magnesium and composite samples' energy absorption was used to measure the toughness property of the samples. It is also necessary to evaluate the ductile or brittle characteristics of the pure magnesium and fabricated composite samples. ASTM D7136 standard was followed for the low-velocity impact test [24].

*2.3.4. Wear Test.* The pin on the disc wear apparatus was used to conduct a wear test, as shown in Figure 3. The wear test was conducted at room temperature under dry sliding conditions according to the ASTM G99-04A standard. Initially, the specimen was polished, and the burrs were removed by emery sheet [25]. The pin size of 8 mm diameter and length of 30 mm were used for the wear apparatus. The wear test was carried out by constant values of sliding at a distance of 1200 m with a force of 20 N and a sliding speed of 500 rpm. The wear rate and coefficient of friction values were observed. The morphology of worn surfaces was captured and analyzed using a scanning electron microscope [26].

## 3. Results and Discussion

*3.1. Tensile Strength.* The tensile test was conducted for three samples of every configuration, and the average values were collected and presented. The variation of tensile strength values by the influence of fly ash reinforcement content is shown in Figure 4. The improvement of elasticity and yield strength was based on the synthesis technique and the percentage of reinforcements. In ceramic reinforcements, the flexibility was improved by grain refinements, texture modification, and nonbasal slip systems [27].

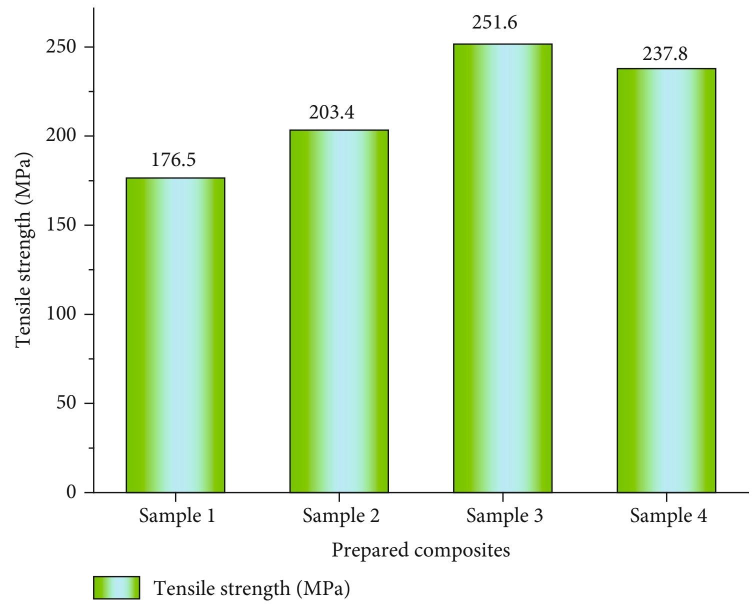



Figure 4: Tensile strength comparison of fabricated metal matrix composites.

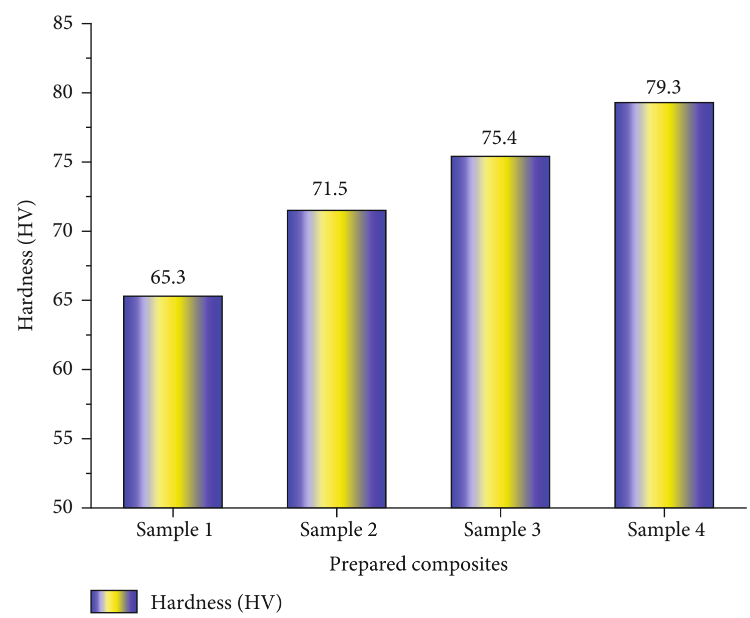



Figure 5: Microhardness results of the fabricated metal matrix composites.

The yield strength is mainly enhanced by the homogeneous distribution of reinforcements, grain refinement, and limited pores in the fly ash-reinforced composites. The fabricated metal matrix composites in sample 3 have higher tensile strength (42% increment) value when compared with pure magnesium, samples 2 and 4. Figure 4 shows the gradual increase in tensile strength up to sample 3; afterwards, its tensile strength value was significantly reduced. Mean tensile strength ± four standard deviations were observed. The fly ash particles in the matrix alloy protect the softer matrix, thus limiting the deformation and also resisting the penetration and cutting of slides on the surface of the composites.

*3.2. Microhardness.* The addition of fly ash reinforcements showed greater improvement in microhardness values of fabricated metal matrix composite samples, as shown in Figure 5.

Sample 4 has an improved hardness value of 21% compared with pure magnesium in sample 1. Hardness values improve due to the equal dispersion of fly ash reinforcement. Hardness results were three times average result of indentation in the Vickers hardness test [28]. The same effects observed in AZ91 Mg/fly ash composites improved hardness value with an increasing percentage of reinforcements [29]. Mean hardness ± 2 standard deviations were observed.

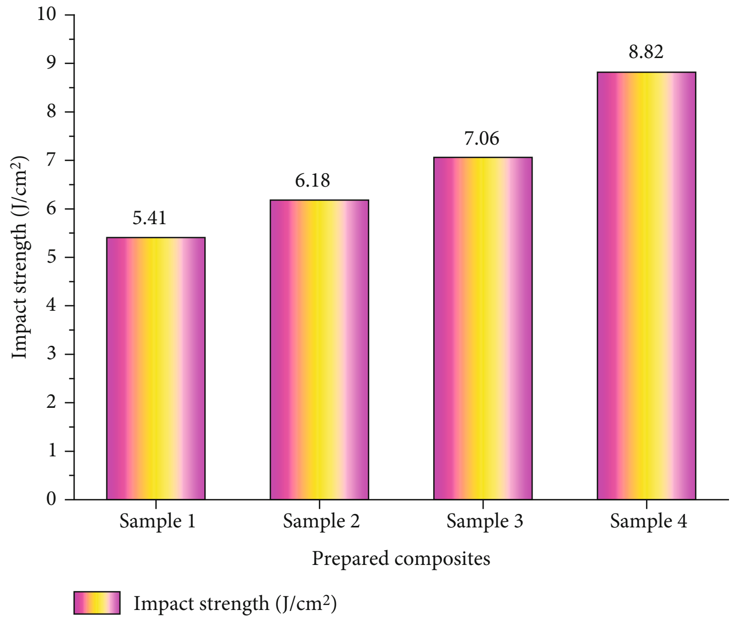



Figure 6: Energy absorption impact strength.

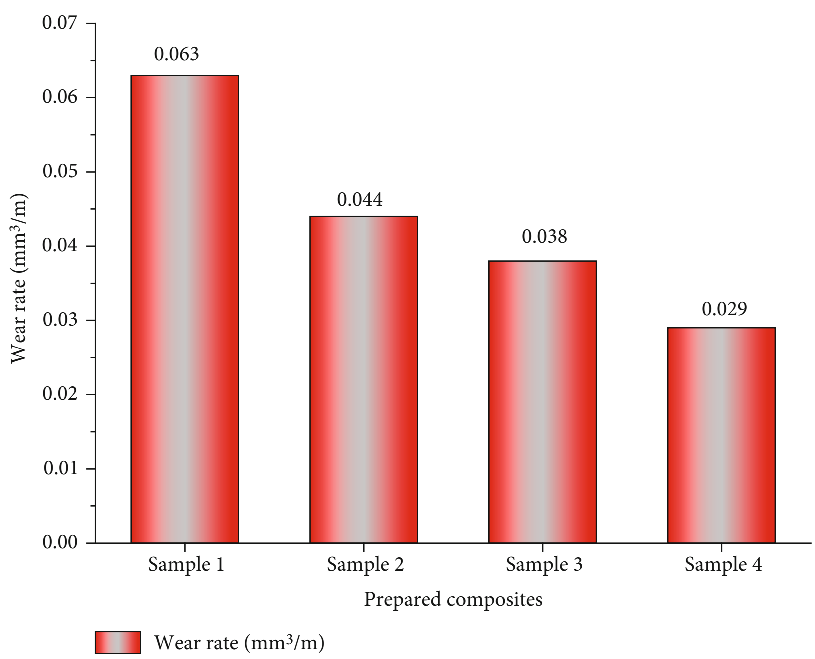



Figure 7: Wear rate of comparison of fabricated metal matrix composite samples.

*3.3. Impact Strength.* The energy absorption results of the samples are presented in Figure 6. It was observed from the result that the inclusion of fillers into the metal matrix gradually improves the energy management of the fabricated metal matrix composites samples. Higher energy absorption can be obtained by enhancing filler percentage. Sample 4 shows a higher energy absorption capacity of 8.82 J/cm$^2$, a remarkable value compared with a pure Mg sample [30]. Mean impact strength ± 0.5 standard deviations were observed.

*3.4. Sliding Wear Behaviour.* The wear test of the proposed samples was conducted at the temperature of 25°C, and the relative humidity was about 50%. The results indicate that wear rates and friction coefficient values decreased with the weight percentage of fly ash, as shown in Figures 7 and 8. There was a remarkable reduction in the wear rate of 53% compared to pure magnesium and sample 4. Similarly, the reduction percentage of wear rate was 13 and 30% vice versa for samples 2 and 3 compared with pure magnesium. The reduced wear rate correlates

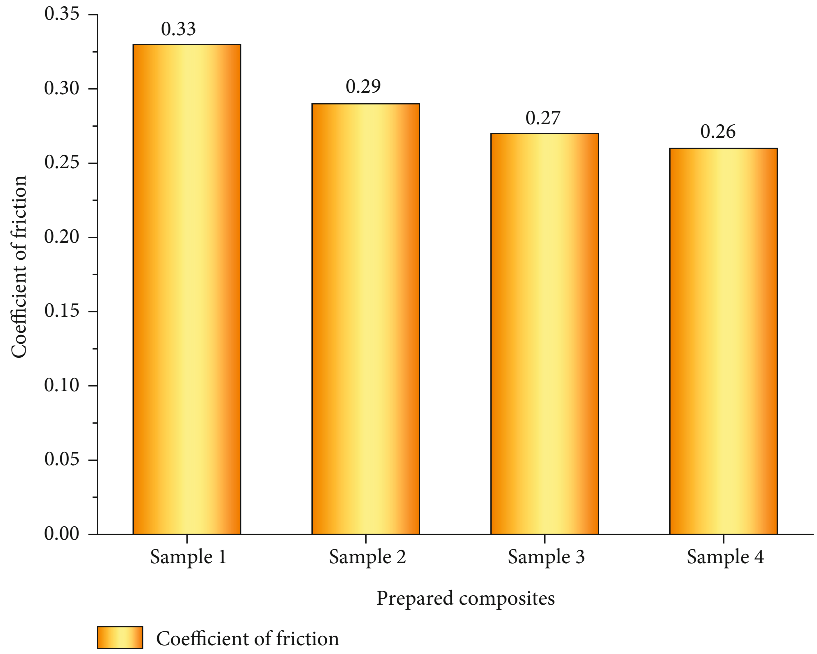



Figure 8: Coefficient of friction of fabricated metal matrix composite samples.

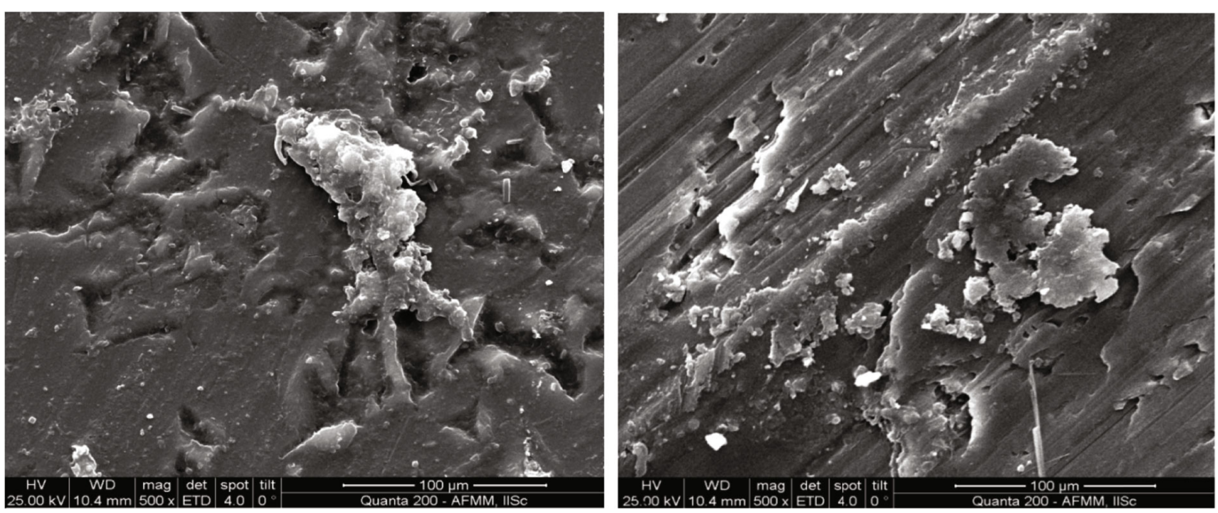
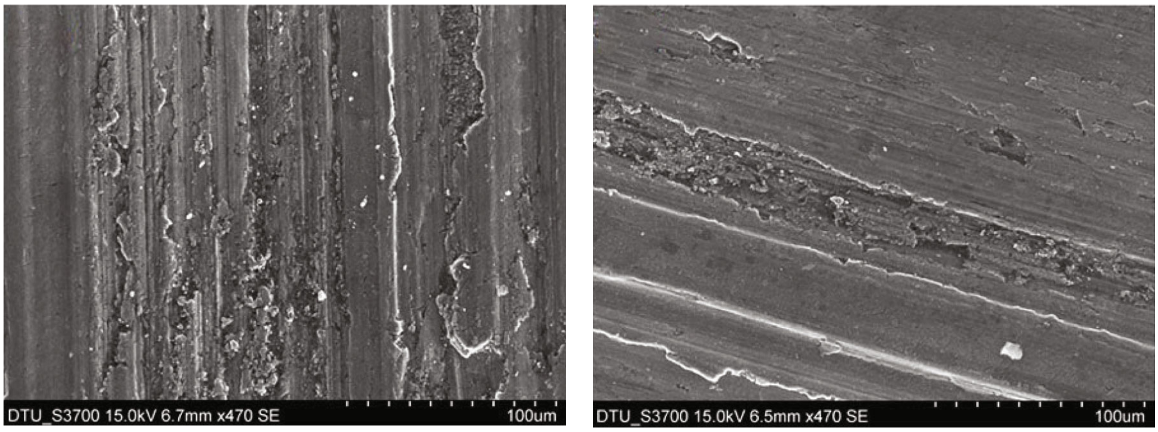



Figure 9: SEM images of pure magnesium samples.

with increased hardness values according to the Archard's wear law of the inverse relationship between wear rate and hardness [31].

*3.5. Scanning Electron Microscope.* The microstructure of pure Mg fabricated using stir casting is shown in Figure 9. The interfacial reaction and oxidation occurred during pure magnesium casting, as displayed in Figure 9. The worn surfaces of pure magnesium and highly reinforced fly ash sample 4 images are shown in Figures 10(a) and 10(b). The worn surfaces represented that the adhesive wear occurred on the unreinforced magnesium. The most important characteristics, such as groove pattern and abrasive wear, were found in the worn surface of SEM images. The craters were created due to applied load and ploughing action on the surfaces in the unreinforced magnesium samples [32]. The wear rates were reduced by adding reinforcements to the samples [33]. The increased load carrying capacity and reduced wear rate on sample 4 were observed, as shown in Figure 10(b). From Figure 10(b), worn surface images observed that smaller craters and grooves evidenced that fly ash fillers influenced improved load carrying capacity and reduced wear rate [34]. The SEM images have shown that the fly ash was homogeneously distributed in magnesium matrix composite [34].




(a) (b)

FIGURE 10: SEM images of worn surfaces of (a) pure magnesium and (b) sample 3.

## 4. Conclusion

This proposed research successfully fabricated pure Mg and fly ash (2.5, 5, and 7.5 wt%) composites. The mechanical properties and wear behaviour on its microstructure were compared between pure Mg and fabricated metal matrix composite samples.

(i) The tensile strength values were improved by 42% in sample 3 compared with pure Mg. Similarly, the hardness values were also improved by 21% in sample 4 compared with pure Mg

(ii) The wear rate and coefficient of friction are also reduced by the increased weight percentage of fly ash reinforcement. The presence of fly ash was beneficial in reducing the wear rates and coefficient of friction

(iii) SEM images show interfacial reactions in fly ash particles during the casting process, concluding that reduced wear rates and improved mechanical properties have favourable responses to wear-resistant applications

## Data Availability

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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